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The Dominant Role of the Crack-tip Mechanical Environment into the Cyclic Response

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Abstract

The process-zone characterization provides an essential pillar in forming the crack stability equation. Thus both, the driving force and the material resistance require comprehensive local exploration in the framework of a global mechanical response envelope. The present study consisted on iron-based single crystals and polycrystalline metastable austenitic stainless steel systems. In both, by following micro-structural and mechanical characterization, fatigue tests have been conducted including load and hydrogen interactions. Assisted by novel techniques, the investigation procedure have been supplemented by ultra fine scale visualization and acoustic emission tracking. Considering the sub-critical crack regime retardation the line profiles of two defined but different process zones have been compared. The single crystal activities provided experimental/theoretical insight into the basic aspects of deformation/hydrogen interaction supported by computational mechanics and simulations. Particularly in interactive cases the combined contribution of mechanical and material science to conceptual issues becomes highly promising.

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Keywords: Load interaction, Hydrogen intaraction, Stainless steel, Phase stability

1. Introduction

Further insights into the fracture process and/or structural integrity issues offer immense technical importance. This in the sense of more general objectives that specify the crack-tip driving force and the material resistance. The aforementioned components provide critical effects on the local crack stability. Griffith in a continuum thermodynamic approach in an elastic system (1) realized that the ideal surface energy component for a global energy balance is always proportional to the fracture area. In elastic-plastic solids the plastic dissipation dominates the mutual interrelationship of the resistance and the driving force become inevadeble. In addition, there is a general recognition that the local driving force G_{local} is modified by the exact crack tip dislocation arrangements. Briefly, the major factors in the fracture

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mechanics crack stability equation depend on the local crack-tip morphology and the given crystallographic situation which by itself is inhomogeneous and anisotropic in nature. Consequently, by considering by the crack-tip mechanical environment the stress intensity factor for the onset of dislocations emission becomes important. Here, various factors emerge, first, in the evaluation of the crack-tip shielding and second, particularly in case of deformation/environment interaction the combined effect of the local stress field and the environment might enhance the crack extension. The present investigation emphasizes partial elements of a broader program regarding the crack-tip perturbation effects on cyclic crack extension and the fracture resistance. The continuous search for transient origins in the framework of the global activities can be divided to a material approach engagement with imposed load interaction effects. For example, extensive research activities have been invested in post-overload behaviour in polycrystalline systems (2-5). Prior activities in iron-based single crystals Chen et al (6) have revealed theoretically and experimentally the important role of the secondary stresses as related to the high sensitivity of cyclic micro-cracking to the local stress field variations. In this context, a modified super-dislocation model has been developed by Lii at al (7) simulating the stages sequence of overload unloads processes and their ramifications on the crack-tip mechanical environment. Single overload may retard or even arrest cyclic sub-critical crack growth depending on the specific overload strength. Load interaction that is achieved by prior overloads (pulses or continuous variable amplitude blocks) provides an extrinsic crack-tip shielding that develops by the affected process zone ahead of the original crack-tip. The monotonic loading behaviour has been extended to cyclic conditions, followed finally in case of phase the composition on top of load interaction.

2. Material and experimental procedures

Various examples were engaged demonstrating some conceptual insights. First, by following a material approach that included poly crystalline Al and iron based alloys (Al-Li, AISI 4340 steel, orthorhombic low symmetry crystal structures alloys) mild steel, stainless steel and superplastic model alloy Zn-22Al. In all these materials single overload were performed using a range of intensification factors. Basically fracture mechanics methodology was utilized and the post single overload fatigue loading that consisted under R=0 and 10 Hz frequency condition, that was monitored covering the total overload affected zone. As such, fatigue crack propagation profiles have been established. In addition Fe-3%Si single crystal study was supplemented. In this case mini-compact fatigue pre-cracked disc specimens were used by applying cyclic tension-tension test with overload corresponding to various intensification factor levels. Particularly in this case ultra-fine features of the crack extension were observed indicating the influence of the affected stress field due to the irregularity of the cyclic spectre. Second, the overload effect was extended to more complex interactive circumstances. For this purpose AISI304 metastable stainless steel was selected. The chemical composition, monotonic mechanical properties, fracture resistance parameters and the steady state fatigue crack propagation rates have been established elsewhere (8). In addition, phase stability aspects in terms of austenite decomposition and martensitic phase's formation have been addressed previously (9). Also here, fracture mechanics methodology was utilized and the process zone nature was modified either by thermal or alternatively by hydrogen interaction. Thus, the polycrystalline system enabled to form a zone of deformed austenite in contrast to a zone of transformed martensitic austenite products. The overloads above or below the Md were kept allowing a constant overload plastic zone size. The subsequent fatigue runs were performed at 296K in constant ΔK. This procedure eliminated the potential effects of raising the driving force due to the crack extension. The third case, iron-based single crystals were selected consisted of Fe-3%Si that beside extensive experimental and simulation program overload effects included also the overload effects.

Gain mini-compact pre-cracked specimens were used and the cyclic crack extension was observed under hydrogen interaction. Following overload to a stress intensity factor level of 26MPam$^{1/2}$ the subsequent cyclic crack extension fracture surface was examined. Here the sub-critical crack regime was enhanced by hydrogen interaction but suppressed by the overload effect. In particular, cyclic fatigue striation were measured in the given {001} <010> crack system. Additional background concerning the cyclic response and overload effects have been elaborated elsewhere (6,7).

3. Experimental results and discussion

The present aforementioned examples demonstrate the role of load or phase stability interaction on the stationary and the sub-critical propagating crack. The crack-tip mechanical environment including the various shielding effects is critical in affecting the mechanical response. Even in microcracking initiation, the incubation time in high strength steel under stress corrosion cracking situation was highly dependent on the exact crack shielding conditions. As addressed by Nakasa et al (10) an increase of delayed failure time was more than one order of magnitude resulted from crack-tip shielding effects. Generally, single overload by open mode stress intensity factor caused crack extension rates retardation. The adopted material approach includes also some of the suspected transient origins and their attributed mechanisms. Again, in the metastable austenitic steels the role of the phase stability was intensively studied and its implications on the mechanical response. As such, it was found that below the Md temperature even with no hydrogen austenite decomposition occurred. However, hydrogen interaction can result in martensitic transformation beside mechanical degradation due to delayed cracking and significant reduction of ductility. For a comprehensive background the austenitic products and the transformation reaction have been established. Supported by X-ray diffraction and Mossbauer spectroscopy analysis indicated that a transformation reaction with hydrogen was γ→έ+ά where, έ and ά are the hexagonal close-packed and the body-centred tetragonal martensitic phases, respectively. With hydrogen during the transient time, hydrogen expanded phase have formed that were identified also as pseudo-phases that were confirmed by internal friction studies (9,11). The comparative study between deformed austenite a multi-phase plastic zone indicated accentuated post overload due to phase stability effects. Beside deformation features in the crack extension wake the overload retardation profile remained consistent. A proposed semi-empirical function could be formulated by

$$\left(\frac{da}{dN}\right)_t = \left(\frac{da}{dn}\right)_{\min} + \left(\frac{da}{dn}\right)_{CA}\left[1 - e^{\frac{-(a_1-a_0)}{\lambda}}\right] \tag{1}$$

Where CA corresponds to the constant amplitude and λ a parameter indicating the recovery degree (12). Accordingly, the differences between the two cases were expressed by λ=6 for the transformed zone and 4 for the deformed austenite zone. The single overload in the Fe-3%Si single crystal was analysed by a super-dislocation modified simulation in assessment of the crack-tip shielding (7). It was shown that the fracture toughness at 273K could be increased by nearly a factor of three with prior single overload at ambient temperature. This monotonic loading behaviour has been extended to cyclic conditions and hydrogen interaction (6). In a sample that was pre-strained to K_I of 26MPam$^{1/2}$ it was found that the subsequent fatigue crack extension kinetics in hydrogen was suppressed to 18MPa. The local reflection of the crack-tip mechanical environment was tracked fractographically. In contrast to almost constant striation spacing with no overload (13) departing from the original crack-tip the fatigue striation spacing were increased gradually. The major concern into the retardation effect explanation is the possible mechanism of closure, blunting, hardening and residual stresses. In the current given case of Fe-3%Si single crystal and hydrogen the physical interpretation becomes easier. First the fatigue crack propagation was relatively smooth following a macro cleavage plane. Second experimental visualization confirmed the consistent sharp crack-tip during the sub-critical crack growth. Thus a model could be developed assuming by cause that closure and blunting was unlikely to the dominant process.

4. Closing remarks, summary and conclusions

The defined crack stability equation that has been clearly formulated by fracture mechanics methodology required further elaboration. The main complexity in the fracture processes are related to real situations that reflect on both the driving force and/or the mechanical fracture resistance. Even more, the driving force and the resistance can hardly be separated physically. And they are interrelated or interwoven due to crack-tip shielding affected also by mechanical perturbations due to various origins. While local residuals or contact stresses as well as crack-tip front morphology affect the driving force this on top of the crack tip dislocation emission. Thus, in elastic-plastic solids, dislocation structure formation phase stability influences that are even enhanced by environmental interaction provide more complex and involved localized events. In this context, the driving force/resistance indicates coupled effects. Although not in the scope of the present paper the phenomenon of Warm Prestressing (WPS) is a typical example associated with materials that are characterised by Ductile-Brittle transition. The current study is centred on two examples in polycrystalline system and one example is iron-based single-crystals. Superimposed load interactions along the sub-critical crack path affect the local crack-tip mechanical environment with implications on the crack stability. The addition of hydrogen/deformation interaction might accentuate multi-phases plastic zone as manifested in metastable austenitic stainless steels. Comprehensive assessment of the mechanical response require a physical viewpoint in local/global eyes in the framework of the material approach. Accordingly the following are concluded.

(1) Development of fundamental aspects associated with the crack-tip shielding potential including crack-tip dislocation emission, phase stability and the complex aspects of interactive effects are illustrated.

(2) The current concern intends to broaden the importance of residuals, contact stress effects, process zone formation and crack growth transient's origins on crack stability.

(3) Crack-tip field perturbations become significant or even accentuated by environmental interaction.

(4) Transients in single crystals might ease the assessments as related to the dominant mechanism of the fracture process.

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